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AFRPL-TR-72-21

(Unclassified Title)

SOLID-PROPELLANT COMBUSTION INSTABILITY SUPPRESSION DEVICES

(Survey of Applications of Mechanical Suppression Devices in Solid-Propellant Rockets)

VOLUME II

W. G. Haymes, W. T. Brooks, W. M. Burkes, et al.

Rocketdyne, A Division of North American Rockwell Corporation
Solid Rocket Division
McGregor, Texas

Technical Report AFRPL-TR-72-21

January 1972

Group 4
Downgraded at 3-Year Intervals
Declassified After 12 Years

[redacted]

Air Force Rocket Propulsion Laboratory
Director of Laboratories
Air Force Systems Command
United States Air Force
Edwards, California

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FOREWORD

Volume 2 of the Final Report on Contract F04611-71-C-0012, a joint effort of the Advanced Projects Department and Solid Rocket Division of Rocketdyne, A Division of North American Rockwell Corporation, was prepared by Solid Rocket Division, McGregor, Texas. Volume 2 documents a survey of applications of mechanical suppression devices in solid propellant rockets. This document carries the contractor's library serial number R-8822-2.

Air Force monitor for this effort is Capt. C. P. Wendelken. Work under the 10-month contract was initiated 7 December 1970.

Publication of this report, which contains classified information extracted from numerous Government and industry releases, does not constitute Air Force approval of the findings or conclusions contained herein. It is published only for the exchange and stimulation of ideas.

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ILLUSTRATIONS

TABLES

INTRODUCTION

(U) A 10-month program entitled "Suppression Devices for Solid Propellant Rocket Combustion Instability" has been performed by the Advanced Programs Department and the Solid Rocket Division of Rocketdyne for the Air Force Rocket Propulsion Laboratory under Contract F04611-71-C-0012. To have the benefit of experience at the outset of this program in the application of mechanical suppression devices to solid rocket combustion instability, one subtask of the contracted effort entailed a survey of past application of such devices. It was intended that, to the degree possible, this survey would provide a description of the suppressors used, information relative to their installation and operating experience, and an indication of their effectiveness.

(U) This report presents results of the survey undertaken. The scope and sources of information used and a summary of the applications of the various types of suppression devices identified are included in subsequent sections.

SCOPE OF SURVEY

(U) A comprehensive (but not necessarily complete) survey of application of suppression devices in rocket motors has been completed. This survey was limited to mechanical suppression devices that generally, for purposes of this discussion, may be grouped into the categories of rods, baffles (including paddles), and acoustic cavities (resonant and non-resonant). The survey was further restricted to relate only to instances involving operational rocket motors or development versions of such motors, where the intention clearly was to incorporate a suppression device ultimately into the motor design.

(U) The principal sources of information for this survey were the "CPIA Motor Manual" (Ref. 1)*, technical reports (both Government and contractor), and discussions with selected individuals. The earlier reviews by Price (Ref. 2, 3, 4**) pertaining to occurrence of combustion instability during rocket motor development programs were especially helpful.

(U) The technical reports reviewed were identified through bibliographies requested from various sources. The primary bibliography used was obtained from the Defense Documentation Center (DDC) covering a time period encompassing the past 25 years. This bibliography cited 386 reports; however, only 41 of these appeared to have relevance to contract objectives, as summarized in Table I. A listing of these specific reports by title is presented in Table II.

(U) To complement the DDC material a similar report bibliography was obtained through North American Rockwell's Technical Information Processing System (NAR-TIPS). This bibliography cited 191 reports. After correlation with the DDC bibliography and screening for relevance, an additional 47 reports were identified for review. These are listed in Table III. A category and relevance summary of these reports is also presented in Table I.

*Identifies references listed at end of report.

**Mr. Price permitted full use of his personal files in regard to this survey. His assistance is gratefully acknowledged.

(U)

TABLE I

REPORT BIBLIOGRAPHY CATEGORY AND RELEVANCE SUMMARY

Relevance Rating*	Category	Number of Reports		
		DDC Bibliography	NAR TIPS Bibliography	Total
1	Motor Experience	14	..	14
2	Suppression Devices	5	4	9
3	Proceedings, Program Reports	9	14	23
4	Mechanism	6	26	32
5	Cold Flow	3	..	3
6	Miscellaneous	4	3	7
	Totals	41	47	88

*Rating of 1 is most relevant

(U)

TABLE II

DDC REPORT BIBLIOGRAPHY, COMBUSTION INSTABILITY SUPPRESSION DEVICES - SUMMARY OF APPLICABLE ENTRIES

Item No.	Description				
	Title	Author(s)	Agency	Date	DDC Ident.
	I. Motor Experience				
1	Qualification Testing of JATO 14-DS-1000	Cohn	WADC	Nov.55	AD-859 951L
2	A/A44A-3 Rocket Motor Development	Zickle	Douglas	Jun.60	AD-319 811
3	Resonance and Unstable Burning in Solid Propellants	McClure, Hart Iberl	JHU/APL	Apr.61	AD-391 489L
4	Experimental Studies of Unstable Combustion in Solid Propellant Rocket Engines	Trubridge, Badham	Imp. Chem. Ind.	Dec.61	AD-283 486
5	Development of Exhaust-Flame Suppression for SIDEWINDER 1C	Breittengrass	NOTS	Dec.61	AD-327 413
6	Development of a Rocket Motor Propellant Charge and Igniter for the Shillelagh Missile System	---	Picatinny	May.62	AD-380 890
7	Development of a Rocket Motor Propellant Charge and Igniter for the Shillelagh Missile System	---	Picatinny	Jan.64	AD-380 992
8	Attenuation of Axial Acoustic Modes in a Model Missile Motor	Buffum, Mathes, Slates, Price	NOTS	Jul.65	AD-619 741
9	Combustion Instability in the DC-MAW Sustainer Motor	Palm	AMICOM	Dec.65	AD-369 192
10	An Experimental Investigation of Some of the Acoustic Attenuation Sources in the TE-M-388 (Iroquois) Rocket Motor	Edwards, Mallick	Thiokol(E)	Feb.66	AD-630 920
11	Explosions and Resonant Burning of Solid Propellant Rocket Motors: An Annotated Bibliography	Hollester	LMSC	May.62	AD-334 966
12	Quality Assurance Tests of Two Minuteman Wing VI Stage III (M57A1) Solid Propellant Rocket Motors at Simulated Altitude Conditions: Tests VI-QA-80 and VI-QH-81 (Motor S/N's 0033396 and 0033417)	Domal, Dougherty	AEDC	Sep.69	AD-504 501
13	Minuteman II Stage III Aft Dome/Convolute Opt Cable Vibration Test	Herber	Boeing	Nov.69	AD-869 440L
14	Suppression of Combustion Instability in Solid Rocket Motors with Propellant Additives and Physical Methods	Brandon	Rohm & Haas	Nov.70	AD-512 093L

*Report in Storage at Rocketdyne

(U)

TABLE II

(Continued)

Item No.	Description				
	Title	Author(s)	Agency	Date	DDC Ident.
	II. Suppression Devices				
15	Study of Gas Oscillations in Half- Open Pipes of Various Shapes. Part 1	Rudinger, Logan	Cornell Aero	Jun.47	AD-495 959
16	Acoustic Losses in a Resonator with Steady Gas Flow	---	Bolt, Beranek, Newman	Jun.64	AD-605 452
17	Analytical and Experimental Investigations of Oscillations in Rocket Motor Baffle Cavities	Torda, Patel	Ill.Inst.Tech.	May.68	AD-835 820
18	Analytical and Experimental Investigations of Oscillations in Rocket Motor Baffle Cavities	Torda, Patel, Bharatan	Ill.Inst.Tech.	Jan.69	AD-849 511
19	Analytical and Experimental Investigations of Oscillations in Rocket Motor Baffle Cavities	Torda	Ill.Inst.Tech.	Jun.70	AD-711 420
	III. Proceedings, Prog. Rpts., etc.				
20	Bulletin of the Thirteenth Meeting of the Joint Army-Navy-Air Force Solid Propellant Group, Held at Congress Hotel, Chicago, Illinois, June 4,5,6,1957	---	CPIA	1957	AD-365 603
21	Interior Ballistics	---	Rohm & Haas	Jul.60	AD-321 239
22	Quarterly Progress Report No. 43, 1 Dec 62--28 Feb 63	---	ABL	Feb.63	AD-336 126L
23	Interagency Chemical Rocket Propulsion Group, Solid Rocket Static Test Working Group - Addendum to Bulletin of the 2nd Meeting October 21-23,1964	---	CPIA	Dec.64	AD-357 805
24	Shock and Vibration Bulletin 34, Part 3	---	NRL	Dec.64	AD-460 001
25	Quarterly Progress Report No. 56, 1 Apr-30 June 66	---	ABL	Jul.66	AD-374 847
26	Interagency Chemical Rocket Propulsion Group, Solid Static Test Working Group Meeting (5th), Oct 18-20, 1967	---	CPIA	Dec.67	AD-386 570
27	Technical Status Report - Apr-Jun 68	---	AMICOM	Jun.68	AD-392 159L
28	Quarterly Progress Report No.	---	BRL	Apr.69	AD-502 506

*Report in Storage at Rocketdyne

(U)

TABLE II
(Continued)

Item No.	Description: Title	Author(s)	Agency	Date	DDC Ident.
	IV. Mechanism				
29	On Acoustic Resonance in Solid Propellant Rockets	McClure, Hart, Bird	JHU/APL	Sep. 59	AD-626 736
30	Solid Propellant Rocket Motors as Acoustic Oscillators	McClure, Hart, Bird	JHU/APL	Oct. 59	AD-626 722
31	Vibration of Thick-Walled Hollow Cylinders Exact Numerical Solutions	Bird, Hart, McClure	JHU/APL	Apr. 60	AD-626 737
32	Vibrations of Thick-Walled Hollow Cylinders: Approximate Theory	Bird	JHU/APL	Apr. 60	AD-626 738
33	Amplification and Attenuation of Sound by Burning Propellants	Hart, Cantrell	JHU/APL	Apr. 62	AD-626 719
34	Response of a Burning Propellant Surface to Erosive Transients	Capener, Dickinson, Marxman	SRI	Apr. 66	AD-634 296
	V. Experimental Cold Flow				
35	Operation Manual for the NOTS-NASA Rocket Motor Acoustic Test Facility Steady-State Resonance Tests with Flow	Buffum, Werbuck, Shear	NOTS	Jun. 67	AD-662 218
36	An Analysis of Axial Acoustic Waves in a Cold Flow Rocket	Culick, Dehority	NWC	Apr. 68	AD-835 043
37	Acoustic Attenuation of the Transverse Travelling Mode in a Cold Combustion Chamber Model	Budden	RPE	Oct. 68	AD-852 440L
	VI. Miscellaneous				
38	Research and Development Work on Pressed Charge Propellants	---	Imp. Chem. Ind.	1956	AD-107 091
39	Research and Development Work on Pressed Charge Propellants	---	Imp. Chem. Ind.	Jun. 56	AD-107 092
40	Application of Static-Test Vibration Data	Trummel	JPL	Aug. 61	AD-264 137
41	An Evaluation of Smoke from Shillelagh Propellants and Other Candidates	Placzek	Rohm & Haas	Aug. 70	AD-510 734L

*Report in Storage at Rocketdyne

(U)

TABLE III

NAR-TIPS REPORT BIBLIOGRAPHY,

COMBUSTION INSTABILITY SUPPRESSION DEVICES

SUMMARY OF APPLICABLE ENTRIES

Item No.	Description			
	Title	Author(s)	Agency	Date
	II. Suppression Devices			
1	Influence of Vent Design on Flow-Dependent Acoustic Losses of a Resonator with Steady Gas Flow, Final Technical Report	Smith, Feldman	Boit, Beranek, Newman	Apr, 66
2	Computer Simulation of High Frequency Combustion Instability and Its Suppression. Final Report.	Bucher	United Aircraft	Apr, 68
3	Suppression of Acoustic Combustion Instability. A Report Bibliography.	---	DDC	Aug, 68
4	Feasibility of a High Performance Fluid Controlled Solid Propellant Rocket Motor	---	Hercules	Jul, 70
	III. Proceedings, Prog. Rpts., etc.			
5	Proceedings of the Interagency Chemical Rocket Propulsion Group Combustion Instability Conference/1st/, 16-20 Nov. 1964, Orlando, Fla., Volume I	---	CPIA	Jan, 65
6	Proceedings of the Interagency Chemical Rocket Propulsion Groups Combustion In-Stability Conference/1st/. 16-20 Nov. 1964, Orlando AFB, Florida, Volume II/U/	---	CPIA	Jan, 65
7	Abstracts of the 2nd Interagency Chemical Rocket Propulsion Group Combustion Conference - 1-5 Nov. 1965	Gunn	CPIA	Sep, 65
8	Interagency Chemical Rocket Propulsion Group 2nd Combustion Conference, 1-5 Nov., Aerospace Corporation, Los Angeles, Calif., Volume 1	---	CPIA	May, 66
9	Interagency Chemical Rocket Propulsion Group 2nd Combustion Conference, 1-5 Nov., Aerospace Corporation, Los Angeles, Calif., Volume 2	---	CPIA	May, 66
10	Combustion Conference, 3rd, Interagency Chemical Rocket Propulsion Group. 17-21 October 1966, John F. Kennedy Space Center NASA Cocoa Beach, Florida. Volume 1	---	CPIA	Feb, 67
11	Combustion Conference, 3rd, Interagency Chemical Rocket Propulsion Group. 17-21 October 1966, John F. Kennedy Space Center NASA Cocoa Beach, Florida. Volume 2	---	CPIA	Feb, 67

(U) TABLE III

(Continued)

Item No.	Description			
	Title	Author(s)	Agency	Date
	III. Proceedings, Prog. Rpts., etc. (Continued)			
12	Annual Supporting Research Report - 1966	---	Hercules	Feb.67
13	4th ICRPG Combustion Conference. Expanded Abstracts and Slides. Volume I	---	CPIA	
14	4th ICRPG Combustion Conference. Expanded Abstracts and Slides. Volume II	---	CPIA	Dec.67
15	5th ICRPG Combustion Conference. Expanded Abstracts and Slides	---	ICRPG	Dec.68
16	6th ICRPG Combustion Conference. Expanded Abstracts and Slides. Volume I	---	CPIA	Dec.69
17	6th ICRPG Combustion Conference. Expanded Abstracts and Slides. Volume II	---	CPIA	Dec.69
18	Solid Propellant Technology. AIAA Reprints, Volume 10	Gross	AIAA	Feb.70
	IV. Mechanism			
19	Experimental Studies of Unstable Combustion in Solid-Propellant Rocket Motors	Landsbaum, Spaid	JPL	Aug.61
20	Interactions Between Finite Amplitude Pressure Waves and a Burning Solid-Propellant Grain. Final Technical Report	Carlson,	Rocketdyne Cano.	Aug.62
21	Low-Frequency Combustion Instability of Solid Rocket Propellants. 1 July - 1 Sept 1962.	Price	NOTS (NWC)	Dec.62
22	Low-Frequency Combustion Instability of Solid Rocket Propellants. 1 Sept - 1 May 1963	Horton, Eisel, Price	NOTS (NWC)	May.63
23	Combustion Instability Research on Solid and Liquid Propellant Rocket Motors at Sheffield University	Swithenbank	Sheffield U. England	Jun.63
24	Low-Frequency Combustion Instability of Solid Rocket Propellants. 1 May 1963 - 31 May 1964	Price, Rice, Crump	NOTS (NWC)	Jun.64
25	Testing the Dynamic Stability of Solid Propellants - Techniques and Data	Horton	NOTS (NWC)	Aug.64

(U) TABLE III

(Continued)

Item No.	Description			
	Title	Author(s)	Agency	Date
	IV. Mechanism (Continued)			
26	Acoustic Absorption Coefficients of the Combustion Products of Aluminized Propellants. Final Report	Ribnich,	Aerochem	Apr,65
27	Research on Combustion of Solid Propellants. Technical Summary Report for the Period 20 April 1965 through 30 June 1966	Muzzy,Brown Steinle,Laren	UTC	Jul,66
28	Effects of Aluminum on Solid-Propellant Combustion Instability	Oberg,Huebner	Rocketdyne Cano	Jul,66
29	Combustion Instability Studies of Extinguishable Propellants	Stepp	Hercules	Sep,66
30	Combustion Instability Studies of Extinguishable Propellants. First Quarterly Progress Report	Stepp	Hercules	Sep,66
31	Combustion Instability Studies of Extinguishable Propellants. Third Progress Report	Stepp,Kramer	Hercules	Jun,67
32	Combustion of Solid Propellants and Low Frequency Combustion Instability	---	NOTS (NWC)	Jun,67
33	Unstable Combustion of Advanced Solid Propellants	Morfey,Temkin	Bolt,Beranek, Newman	Sep,67
34	Research on Combustion of Solid Propellants. Technical Summary Report for the Period 1 July 1966 through 31 August 1967	Muzzy	UTC	Oct,67
35	Combustion Instability Studies of Extinguishable Propellants. Final Report	Stepp,Miller, Yount,Angelus	Hercules	Mar,68
36	The Low-Pressure Combustion of Solid Propellants, Summary of a Study of	Strand	JPL	Apr,68
37	Combustion of Solid Propellants and Low Frequency Combustion Instability. Progress Report	---	NOTS (NWC)	Apr,68
38	A comparison of Analysis and Experiment for Solid Propellant Combustion Instability	Beckstead, Culick	NWC	May,68
39	Acoustic Admittance Measurements	Brandon, Wood	Rohm & Haas	Jun,68

(U)

TABLE III

(Continued)

Item No.	Description			
	Title	Author(s)	Agency	Date
	IV. Mechanism (Continued)			
40	Measurement Problems Related to Solid Rocket Combustion Instability	Mathes	NWC	Jul,68
41	Low-Frequency Combustion Instability. Progress Report	Mathes,Boggs Dehority	NWC	Dec,68
42	Experimental Studies on the Oscillatory Combustion of Solid Propellants	---	NWC	Mar,69
43	Nonlinear Acoustics of Unstable Combustion Phenomena	Lee,Ungar	Bolt,Beranek, Newman	Feb,69
44	T-Burner Manual	---	CPIA	Nov,69
	V. Miscellaneous			
45	Investigation of Solid Propellant Burning Rate Control by Acoustic Means. Final Report	Elias	Acoustica Associates	Sep,63
46	Propellant Combustion Phenomenon During Rapid Depressurization	Capener, Dickinson, Marxman	Stanford Research Institute	Sep,66
47	Development of Propellants Containing an Energetic Oxidizer	Rudy	UTC	Dec,66

SUPPRESSION DEVICE APPLICATIONS

(U) Results of the survey are summarized in Table IV which identifies the motors and relevant propellant, design, and suppression device data applicable to each. Results of the survey are further discussed in the ensuing paragraphs by the suppression device categories previously noted.

RODS

(U) Included in this category are those devices installed in the grain perforation(s) that are characterized by a large length-to-transverse dimension ratio and whose transverse dimensions are balanced about the longitudinal centerline and are relatively small compared to dimensions of the grain perforation. Thus, the so-called resonance paddles are arbitrarily excluded from this category and included under the category of baffles.

(U) The number of applications of resonance rods far outnumber the application of the other types of devices. Of the 59 instances noted in Table IV, 49 have involved this type of device. As far as can be ascertained, the instability involved has been in the transverse modes. Presumably the rods have been relatively effective in the applications cited.

(U) These applications have involved a variety of installation features. The rods have been both cantilivered from one end and supported from both ends of the motor. Various rod cross-sections have been used; including circular, square, rectangular, cruciform, and "Z" shapes. Rods have been installed both partway and for the full length of the grain perforation.

(U) Table V presents a summary of resonance rods applications in terms of pertinent motor features. As can be noted their use has been, with one exception, in motors with double-base propellant. It is interesting to note that they have been successfully used with a wide variety of grain designs. Because of the nature of the double-base propellants involved in these motors the propellant grains have been cartridge loaded rather than case bonded.

(U) In summary, the survey indicates that resonance rods have had a wide and relatively successful application in the suppression of transverse modes of instability. Their use in large measure has been based on empirical knowledge gained from experience rather than rational design methods based on a fundamental understanding of the suppression mechanism.

(C)

TABLE

MECHANICAL COMBUSTION INST

	ITEM	DEVEL AGENCY	IDENTIFICATION COMPANY	IDENTIFICATION MILITARY	APPLICATION	PERFORMANCE(a) THRUST, LB	PERFORMANCE(a) PRESS., PSIA	PERFORMANCE(a) TIME, SEC	ENVELOPE(b) DIA, IN.	ENVELOPE(b) L., IN.	PROPELLANT DESIGNATION	PROPELLANT TYPE(c)
RODS	1	PICATINNY		M3	DRONE BOOSTER	2,645	1300	0.69	5.01	13.71	M16(T6)	DB
	2	ABL	X217A1			7,600	1060	1.72	8.012	47	OIO	DB
	3	ABL	X223A1	MK 6 MOD 0	ORIOLE BOOSTER	8,576	1060	2.19	11.00	29.29	OIY	DB
	4	PICATINNY		T50	MATADOR BOOSTER	47,323	1001	2.37	2.05	100	T 16	DB
	5	PICATINNY		T52	LA CROSSE MOTOR	34,250	1120	2.85	15.70	76.16	T-16	DB
	6	BELL AIRCRAFT	X221A1		METEOR MOTOR	965	1105	0.64	8.25	21.32	OIY	DB
	7	ABL	X225A1		METEOR BOOSTER	6,245	902	3.46	8.109	57.3	OIO	DB
	8	ABL	X219A2		TALOS BOOSTER	86,590	1010	4.11	30.125	66	OIY	DB
	9	PICATINNY		T34	JATO	4,307	1058	31.6	21.75	60.5	OGK	DB
	10	ABL	X218A1		TERRIER SUSTAINER	2,862	585	33.3	15.000	55.21	ALL	DB
	11	ABL	X230A3		TALOS BOOSTER	112,100	1030	3.00	30.10	84.65	OIY	DB
	12	IMP CHEM	E501C1		BULLDOG BOOSTER	44,000	1040	2.56	16.30	107.4	OIO	DB
	13	ABL	X224A1, B1		ADV TERRIER BOOSTER	63,112	991	4.19	21.073	122.81	OIO	DB
	14	IMP CHEM	E514A1		BOOSTER	21,100	965	2.83	11.776	114.85	OIO	DB
	15	ABL		M8	JATO	1,090	1070	12.7	9.38	25.72	OGK	DB
	16	ABL	X217C1	MK 1 MOD 0	TORPEDO BOOSTER	6,583	975	1.8	8.00	44.0	OIO	DB
	17	IMP CHEM	E513B1, P1, S1		BOOSTER	19,200	1220	3.22	11.776	104.2	SRS 1/25	DB
	18	ABL	X239B2	MK 11 MOD 1	TALOS BOOSTER	99,300	865	5.30	30.125	103.9	ARP/AHH	DB/DB
	19	IMP CHEM	E512A1		SEASLUG SUSTAINER	3,000	605	35.5	16.00	103.65	AID(M11)/5, OIO/2K/5	DB/DB
	20	ABL	X239A2		TALOS BOOSTER	107,540	965	4.93	30.125	103.9	ARP/AHH	DB/DB
	21	ABL	X236A2		TARTAR MOTOR	14,350/2,475	1990/360	3.61/16.92	13.5	82.038	BHQ/BIC	DB/DB
	22	ABL	X242A1		ASROC BOOSTER	11,100	1020	3.65	11.650	56.375	ARP	DB
	23	ABL	X235A3	XM 26	LITTLE JOHN MOTOR	31,460	1193	1.50	12.5	100.0	ARP	DB
	24	ABL	X240A1		TERRIER BOOSTER	62,000	1220	3.93	18.060	120.15	ARP/AHH	DB/DB
	25	ABL	X233A2		TALOS BOOSTER	122,000	1040	4.60	30.125	103.9	ARP/AHH	DB/DB
	26	ABL	X213J3A	MK 5 MOD 0	TERRIER SUSTAINER	2,305	1150	28.0	13.500	43.657	OGK	DB
	27	ABL	X234A3		ADV TERRIER SUSTAINER	2,140	555	29.5	13.510	54.153	BLG/CLK	DB/DB
	28	AEROJET		MK 7 MODS 1, 2, 3	JATO	4,375	644	5.50	9.38	43.38	AN 504J	AP/P-S
	29	ABL	X234C5	MK 7 MOD 0	TERRIER SUSTAINER	2,115	720	28.2	13.5	60	CQE	DB
	30	ABL	X251C1	MK 11 MOD 2	TALOS BOOSTER	100,000	975	5.250	30.112	100	ARP/AHH	DB/DB
	31	ABL	X256A1	MK 12 MOD 1	TERRIER BOOSTER	60,500	1134	4.030	18.0	120	CAP/AHH	AL-DB/DB
	32	ABL	X216E6, F6	MK 7 MOD 0	TERRIER BOOSTER	49,550	1103	2.80	16.2	106	OIO	DB
	33	NOTS		MK 16 MODS 0, 1, 2	ZUNI	6,520		1.045	5.0	62	STD X-8	DB
	34	PICATINNY		M95	LINE CHARGE	1,240	1045	4.653	6.29	28.09	T 16	DB
	35	IMP CHEM	E515B2		VR 725 SUSTAINER	3,020	695	39.7	17.36	101.5	AID(M15)/5 OIO/N2P/5	DB/DB
	36	IMP CHEM	E520A3		SEASLUG SUSTAINER	4,100	700	35.9	16.00	103.43	AID(M15)/4, AID(M15)/5, OIP/N2P/4, OIO/N2P/5	DB/DB
	37	ABL	X220A9	MK 1 MOD 0	DEACON	6,070	1040	2.75	6.250	101.099	OIY	DB
	38	PICATINNY		T9E2, M4	MOTOR FOR DETONATING CABLE	240	1210	0.46	1.90	8.56	T2	DB
	39	ABL	X240B4	MK 12 MOD 0	ADV TERRIER BOOSTER	66,000	1206	3.978	18.0	120.15	CAP/AHH	AL-DB/DB
	40	ABL	X226A3	MK 9 MOD 0	SHARK BOOSTER	125,904	975	3.70	27.175	154	OIO	DB
	41	APL	X216A2	M88	NIKE-HERCULES BOOSTER	46,000	900	2.80	17.57	105.5	OIO	DB
	42	ABL	X244B3	M31A1	IMP HONEST JOHN MOTOR	117,420	1255	3.10	27.75	134	ARP	DB
	43	ABL	X235D1	M26	LITTLE JOHN MOTOR	33,623	1115	12.02	12.02	77.51	ARP	DB
	44	PICATINNY		M37A1	IMP HONEST JOHN SPIN ROCKET	2,260	1670	0.172	3.25	10.57	X8	DB
	45	ABL	X223B3	MK 8 MOD 0	BULLPUP SUSTAINER	8,311	1039	2.26	11.00	29.20	OIY	DB
	46	ABL	X214B3	MK 6 MOD 0	BOAR BOOSTER	14,000	965	2.47	12.59	57.11	OIO	DB
	47	ABL	X261A5	MK 13 MOD 0	POLARIS GAS GENERATOR		2175	0.54	18.0	40.62	EDD	DB
	48	PICATINNY		M3A2E1	DRONE BOOSTER	2,700	1730	0.673	5.12	13.73	M21	DB
	49	NWC		MK 4 MODS 6, 8 MK 40 MODS 0, 1	FFAR	760	1210	1.42	2.75	31.60	N-5	DB
BAFFLES	50	ABL	X241A1		VANGUARD 3RD STAGE	2,620	195	34.5	17.98	39.27	BUU	AL-DB
	51	ABL	X240A5	XM69	ALTAIR I 3RD STAGE DELTA	2,850	190	38.9	18.0	44.20	BUU	AL-DB
	52	ABL	X254A1	XM70	ANTARES 3RD STAGE SCOUT	14,100	285	37.1	30.05	76.13	BUU	AL-DB
	53	MICOM			DC-MAW SUSTAINER MOTOR	917	1600	1.2	4.2	10.5	X-14	DB
	54	HERCULES		M57A1	MINUTEMAN 3RD STAGE	17,085	245	51.0	37.9	70.0	CYH 77 DDP 77	CMDB
	55	ROCKETDYNE	RS-B-539		SAM MOTOR	962/244	1950/515	1.51/2.74	2.75	32.0	RDS-545/RDS 507	CTPB
CAVITIES	56	AEROJET	A/A 44A-3		GENIE MOTOR	35,050	1400	2.15	15.0	54.0	ANP 2910BI	PU
	57	AEROJET		MK 58	ADV. SPARROW MOTOR							
	58	ROCKETDYNE	RS-B-538		SAM MOTOR	1000/215	2060/430	1.44/3.16	2.75	32.0	RDS [illegible]	CTPB
	59	HERCULES		M57A1	MINUTEMAN 3RD STAGE	17,085	245	51.0	37.9	70.0	CYH 77 DDP 77	CMDB

(a) APPROXIMATE VALUES AT 70 F

(b) APPROXIMATE OUTSIDE DIMENSIONS OF COMBUSTION CHAMBER

(c) DB DOUBLE BASE AP P S AMMONIUM PERC

CMDB COMPOSITE MODIFIED DOUBLE BASE

PU POLYURETHANE COMPOSITE

Rocketdyne
North American Rockwell

TABLE IV

MBUSTION INSTABILITY SUPPRESSION DEVICES

PROPELLANT		GRAIN		SUPPRESSION DEVICE		REMARKS
DESIGNATION	TYPE(1)	DESIGN	LOADING	TYPE	DESCRIPTION	
…(T6)	DB	ASSEMBLY 7 TUBES	CARTRIDGE	RODS		
…O	DB	MULTIPERFORATED	CARTRIDGE	RODS		
…Y	DB	MULTIPERFORATED	CARTRIDGE	RODS		
…-16	DB	ASSEMBLY 12 TUBES	CARTRIDGE	RODS	RECTANGULAR CROSS SECTION (?)	
…-16	DB	ASSEMBLY 7 TUBES	CARTRIDGF	RODS		
…Y	DB	SLOTTED TUBE	CARTRIDGE	ROD		
…O	DB	4-SPOKE WAGON WHEEL	CARTRIDGE	RODS		
…Y	DB	MULTIPERFORATED	CARTRIDGE	RODS		
…K	DB	SLOTTED TUBE	CARTRIDGE	ROD		
…LL	DB	SLOTTED CYL CYL	CARTRIDGE	ROD		SUBSONIC BLAST TUBE
…Y	DB	MULTIPERFORATED	CARTRIDGE	RODS		
…O	DB	MULTIPERFORATED	CARTRIDGE	RODS		
…O	DB	MULTIPERFORATED	CARTRIDGE	RODS		
…O	DB	MULTIPERFORATED	CARTRIDGE	RODS		
…K	DB	SEGMENTED CYL	CARTRIDGE	ROD		
…O	DB	MULTIPERFORATED	CARTRIDGE	RODS		
…S 1/25	DB	3-SPOKE WAGON WHEEL	CARTRIDGE	RODS		
…RP/AHH	DB/DB	DUAL PROPELLANT 4-SPOKE WAGON WHEEL	CARTRIDGE	RODS		
…IO(M11)/5 OIO/7K/5	DB/DB	2 TANDEM SLOTTED TUBES	CARTRIDGE	RODS		SUBSONIC BLAST TUBE
…RP/AHH	DB/DB	8-SPOKE WAGON WHEEL	CARTRIDGE	RODS		
…IQ/BIC	DB/DB	DUAL PROPELLANT SLOTTED TUBE	CARTRIDGE	ROD		SUBSONIC BLAST TUBE
…P	DB	SLOTTED TUBE	CARTRIDGE	RODS		FLAT END CLOSURE WITH MULTINOZZLES
…P	DB	4-SPOKE WAGON WHEEL	CARTRIDGE	RODS		
…P/AHH	DB/DB	MOD. 2-POINT STAR	CARTRIDGE	RODS	SQUARE CROSS SECTION (?)	
…P/AHH	DB/DB	DUAL PROPELLANT 8-SPOKE WAGON WHEEL	CARTRIDGE	RODS		
…K	DB	SLOTTED TUBE	CARTRIDGE	ROD		SUPERSONIC BLAST TUBE
…G/CLK	DB/DB	SLOTTED TUBE	CARTRIDGE	ROD		
…-584J	AP/P.S	ROD AND TUBE	CARTRIDGE	RODS	SQUARE CROSS SECTION (?)	
…K	DB	SLOTTED TUBE	CARTRIDGE	ROD		SUBSONIC BLAST TUBE
…P/AHH	DB/DB	DUAL PROPELLANT 8-SPOKE WAGON WHEEL	CARTRIDGE	ROD		
…P/AHH	AL-DB/DB	DUAL PROPELLANT MOD. 2-POINT STAR	CARTRIDGE	RODS		PROPELLANT ALUMINUM CONTENT 5%
	DB	MULTIPERFORATED	CARTRIDGE	RODS		
… X-8	DB	8-POINT STAR	CARTRIDGE	ROD	CRUCIFORM CROSS SECTION	
…A	DB	INTERNAL-EXTERNAL TUBE	CARTRIDGE	ROD	SQUARE CROSS SECTION	
…(M15)/5 …N2P/5	DB/DB	SLOTTED TUBE	CARTRIDGE	ROD		SUBSONIC BLAST TUBE
…(M15)/4, AIO(M15)/5, …N2P/4, OIO/N2P/5	DB/DB	SLOTTED TUBE	CARTRIDGE	RODS		SUBSONIC BLAST TUBE
	DB	8-POINT STAR	CARTRIDGE	ROD		
	DB	INTERNAL-EXTERNAL TUBE	CARTRIDGE	RODS		
…P/AHH	AL-DB/DB	DUAL PROPELLANT MOD. 2-POINT STAR	CARTRIDGE	RODS		PROPELLANT ALUMINUM CONTENT 5%
	DB	MULTIPERFORATED	CARTRIDGE	RODS		
	DB	MULTIPERFORATED	CARTRIDGE	RODS		
	DB	4-SPOKE WAGON WHEEL	CARTRIDGE	RODS	CRUCIFORM CROSS SECTION	
	DB	4-SPOKE WAGON WHEEL	CARTRIDGE	RODS	"Z" CROSS SECTION	
	DB	ASSEMBLY 7 TUBES	CARTRIDGE	RODS		
	DB	MULTIPERFORATED	CARTRIDGE	RODS		
	DB	MULTIPERFORATED	CARTRIDGE	RODS		
	DB	MULTIPERFORATED	CARTRIDGE	RODS		
	DB	ASSEMBLY 7 TUBES	CARTRIDGE	RODS		
	DB	8-POINT STAR	CARTRIDGE	ROD		
…U	AL DB	SLOTTED TUBE	CASE BONDED	BAFFLE	LONGITUDINAL PADDLE	PROPELLANT ALUMINUM CONTENT, 2.9%
…U	AL DB	SLOTTED TUBE	CASE BONDED	BAFFLE	LONGITUDINAL PADDLE	PROPELLANT ALUMINUM CONTENT, 2.9%
…U	AL DB	SLOTTED TUBE	CASE BONDED	BAFFLE	LONGITUDINAL PADDLE	PROPELLANT ALUMINUM CONTENT, 2.9%
…4	DB	SLOTTED TUBE	CARTRIDGE	BAFFLE	LONGITUDINAL PADDLE WEB INSERTS	
…H 77 OCP 77	CMDB	SLOTTED TUBE END BURNER	CASE BONDED	BAFFLE	LONGITUDINAL PADDLE	
…S-545 PDS 507	CTPB	TUBE	CASE BONDED	BAFFLE	TRANSVERSE ORIFICE	PROPELLANT AL CONTENT, 16% AND 5%
…P 29160	PU	12 POINT DENDRITE	CASE BONDED	CAVITY	ARRAY UNTUNED HOLES ON AFT CLOSURE	
				CAVITY	HELMHOLTZ RESONATOR (?)	
…S-545	CTPB	WAGON WHEEL TUBE	CASE BONDED	CAVITY	HELMHOLTZ RESONATOR	PROPELLANT ALUMINUM CONTENT 16%
[illegible]	CMDB	SLOTTED TUBE END BURNER	CASE BONDED	CAVITY	HELMHOLTZ RESONATOR	

[illegible] AP/P.S - AMMONIUM PERCHLORATE POLYESTER STYRENE AL DB - ALUMINIZED DOUBLE BASE
[illegible] MODIFIED DOUBLE BASE CTPB - CARBOXY TERMINATED POLYBUTADIENE COMPOSITE
[illegible]

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(U) TABLE V

SUMMARY OF RESONANCE ROD APPLICATIONS AND MOTOR DESIGN FEATURES

Total Number of Applications--49	
Feature	Number of Instances
Propellant Type	
AP/Polyester-Styrene	1
Double Base	46
Aluminized Double Base	2
Grain Configuration	
Multiperforated	14
Wagon Wheel	9
Star	6
Slotted Tube	11
Rod and Tube	1
Internal/External Tube	2
Segmented Cylinder	1
Multicylinder Assembly	5
Grain Loading and Retention	
Cartridge	49

BAFFLES

(U) This category encompasses those devices that project into the internal flow of the rocket motor. They are characterized by relatively large plane areas that can be placed in the internal flow with desired orientation as to mean flow and oscillatory motion. Applications to date have included both longitudinally and transversely oriented baffles.

(U) The number of application of baffles in solid propellant motors are much fewer than has been the case with resonance rods. This survey has identified six instances where baffles have been used. Five of these involved longitudinal baffle orientation, with the other being a transverse installation.

(U) The five applications of longitudinal baffles are identified as Items 50, 51, 52, 53, and 54 in Table IV. In four of the five instances the instability was primarily in the transverse modes. The baffles used in these instances were presumably generally effective in suppressing the instability. The first three pertain to the VANGUARD third-stage, ALTAIR I, and ANTARES motors. The design characteristics of these motors are similar. The grain configuration is a slotted-tube, case-bonded configuration of aluminized double-base propellant. The baffles in each were similar and in the configuration sometime termed a resonance

(U) paddle. The installation for the VANGUARD third-stage motor is shown in Fig. 1. This configuration of the device consists basically of a flat rectangular member oriented along the motor axis with its transverse dimension nearly as large as the initial cylindrical perforation diameter. This rectangular element is fixed in place by suitable structural members cantilevered from the forward head.

(U) The fourth application of longitudinal baffles noted (Item 53 of Table IV) involved developmental testing in the DC-MAW sustainer motor. The propellant in this motor is double-base and configured, also, into a slotted-tube design. Baffles similar to those just described and, alternately, cast into the grain web were evaluated. All of these approaches were effective (Ref. 5).

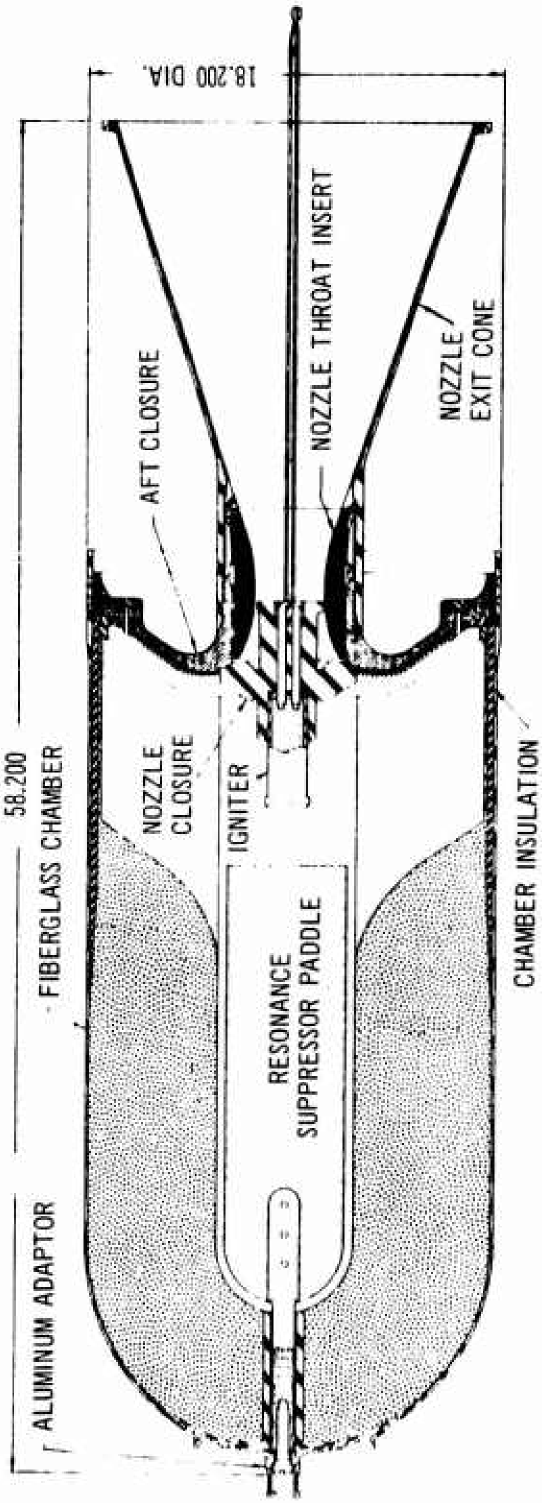
(U) The fifth application of a longitudinal baffle identified was relatively recent and in connection with an evaluation of its potential effectiveness in suppression of oscillations in the Minuteman III, Third Stage M-57A1 motor (Item 54 of Table IV). The application was unique in that a longitudinal baffle was used with oscillations predominately in the longitudinal mode. The installation is shown in Fig. 2. The effectiveness of the baffle in the single test conducted was obscured by other test difficulties. No further evaluation has apparently been accomplished (Ref. 6).

(U) The only instance of application of a transverse baffle identified was by Rocketdyne in connection with suppression of longitudinal mode instability in a small, tactical dual-thrust rocket motor (Item 55 of Table IV). The initial installation consisted of three baffles, each in the form of a center-perforated disc, oriented transversely and placed at selected locations in the motor as shown in Fig. 3. This configuration effectively eliminated the severe instability present in this motor. Subsequent testing has demonstrated equally effective suppression by means of a single baffle of the same general design.

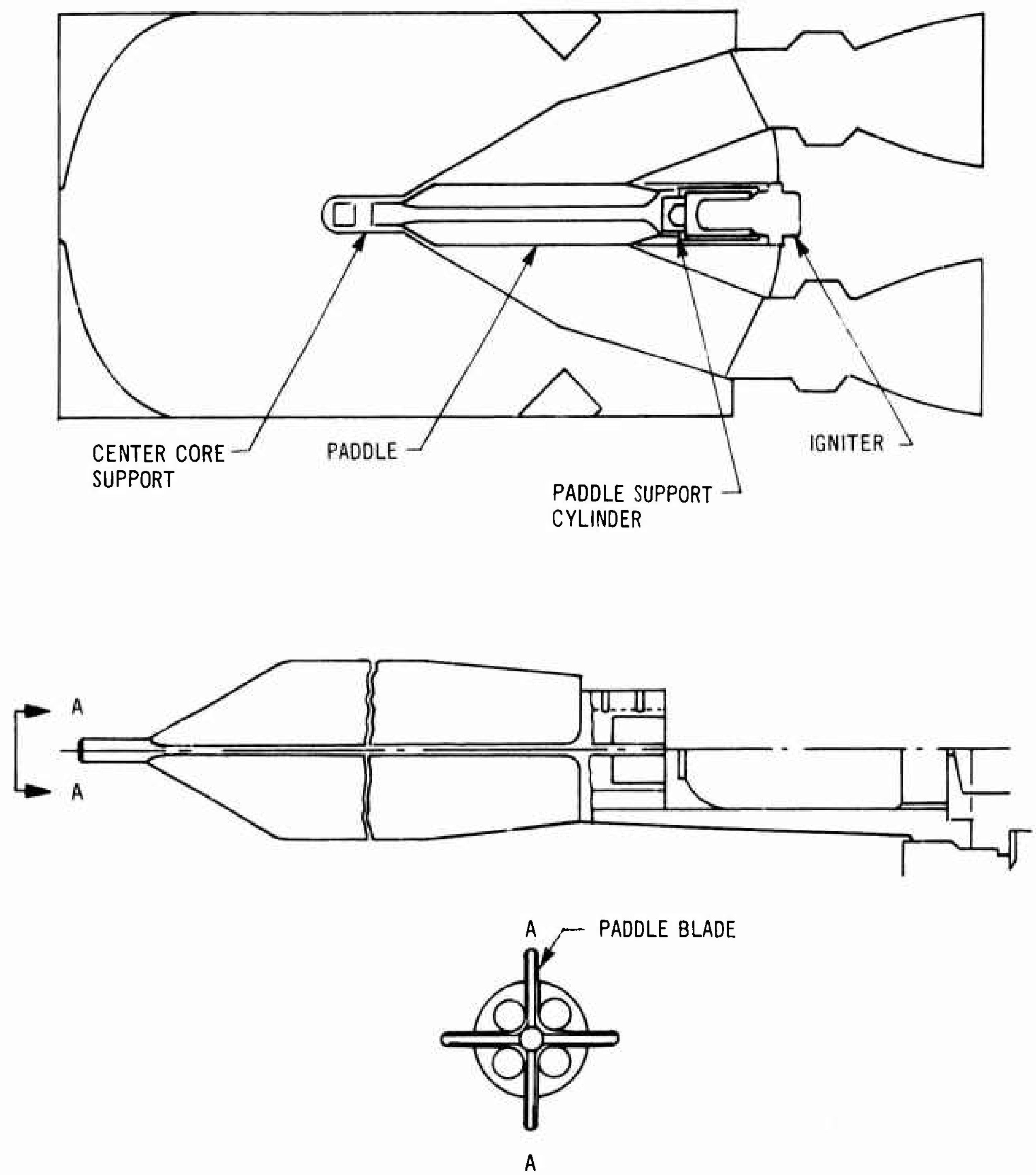
ACOUSTIC CAVITIES

(U) Four instances of application of acoustic cavities to suppress oscillatory combustion have been identified. In all cases they have been used to suppress instability in the longitudinal mode.

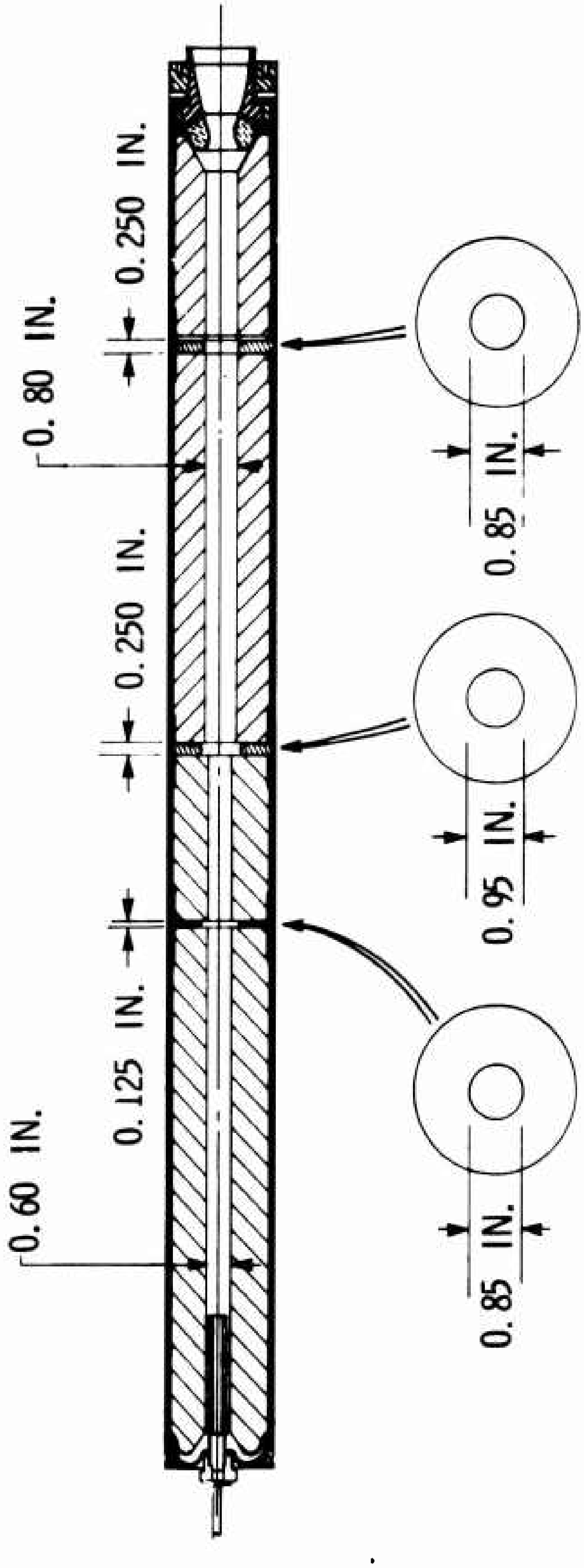
(U) The first use of acoustic cavities noted in this survey was in connection with an improved version of the A-A44A-1 motor (Item 56, Table IV). The suppressor used here was an untuned configuration consisting of several hundred small blind holes with axes parallel to the motor centerline placed in the aft closure insulation. Although the oscillations were not completely suppressed the amplitudes were reduced to about 85% of their former levels (Ref. 7).



(C) Figure 1. Longitudinal Baffle (Paddle) in VANGUARD Third Stage Motor



(U) Figure 2. Longitudinal Baffle Installed in Hercules Minuteman III Third Stage Motor (M-57A1)



(U) Figure 7. Application of Transverse Baffles in Rocketdyne Dual Thrust Rocket Motor

(U) The last three applications (Items 57, 58, and 59 of Table IV) of cavities noted have been relatively recent. These have all involved the use of Helmholtz resonators. One of these is the Advanced SPARROW (Mk 58) motor; but it has not been possible to develop the details of this installation and its effectiveness. The use of a Helmholtz resonator in a small tactical motor has been previously reported by Rocketdyne (Ref. 8). This installation is shown in Fig. 4. Although combustion oscillations were not completely suppressed, the severe instability present in the motor resulting in unpredictable increases in mean pressure and thrust levels was eliminated and the amplitude of the residual oscillations were less than 10% of previous levels. The third use of a Helmholtz resonator was in connection with the third stage motor (M-57A1) of Minuteman III (Ref. 6). In this motor the suppressor was integrated with the igniter on the aft motor closure as shown in Fig. 5. The effectiveness of the resonator was not as good as anticipated. However, because of the complicated grain perforation, the resulting mode shape, and the physical restraints associated with orientation of the resonator the location of the resonator apertures was not optimum relative to the pressure antinode. This fact, undoubtedly was significant in regard to unsatisfactory suppression performance obtained.

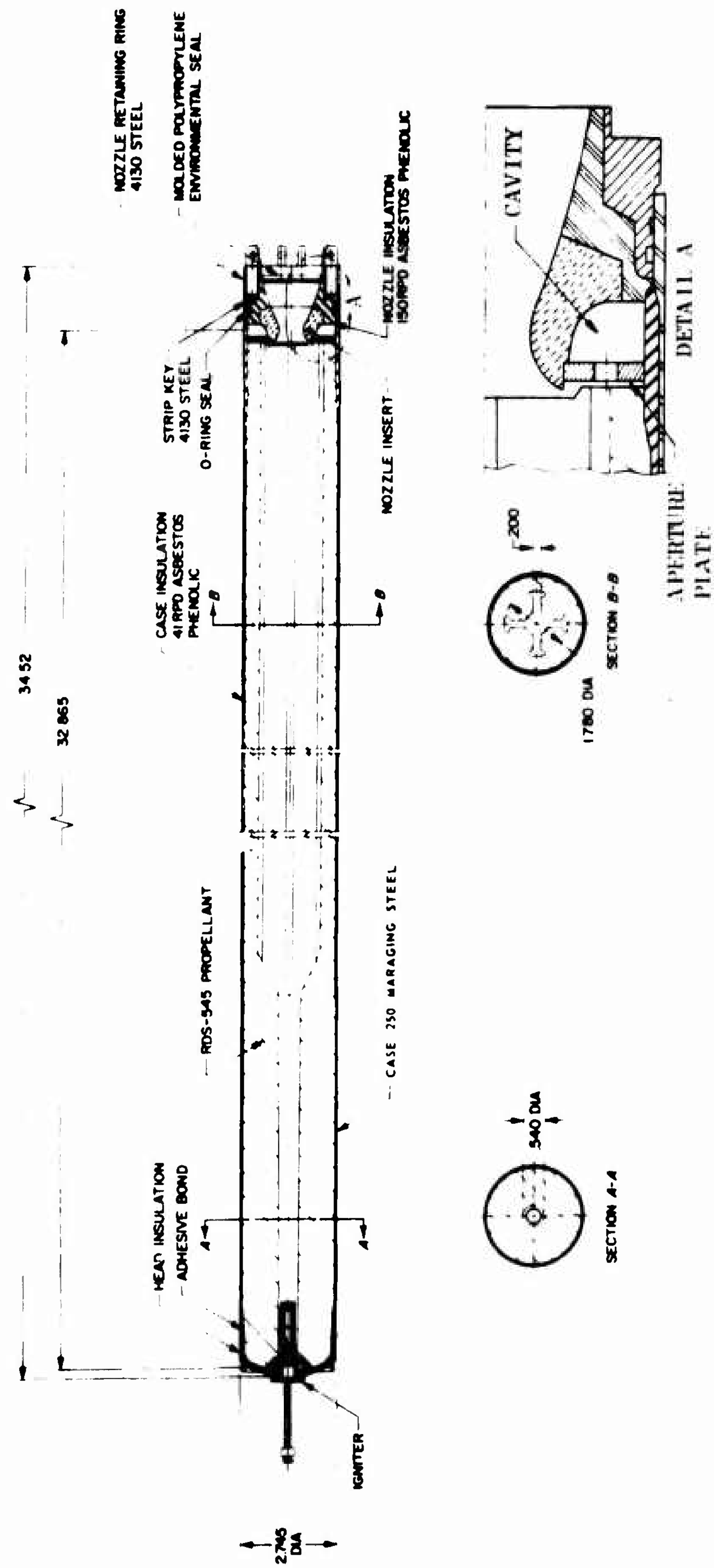


Figure 4. Helmholtz Resonator Installation in Rocketdyne Dual Thrust Rocket Motor (C)

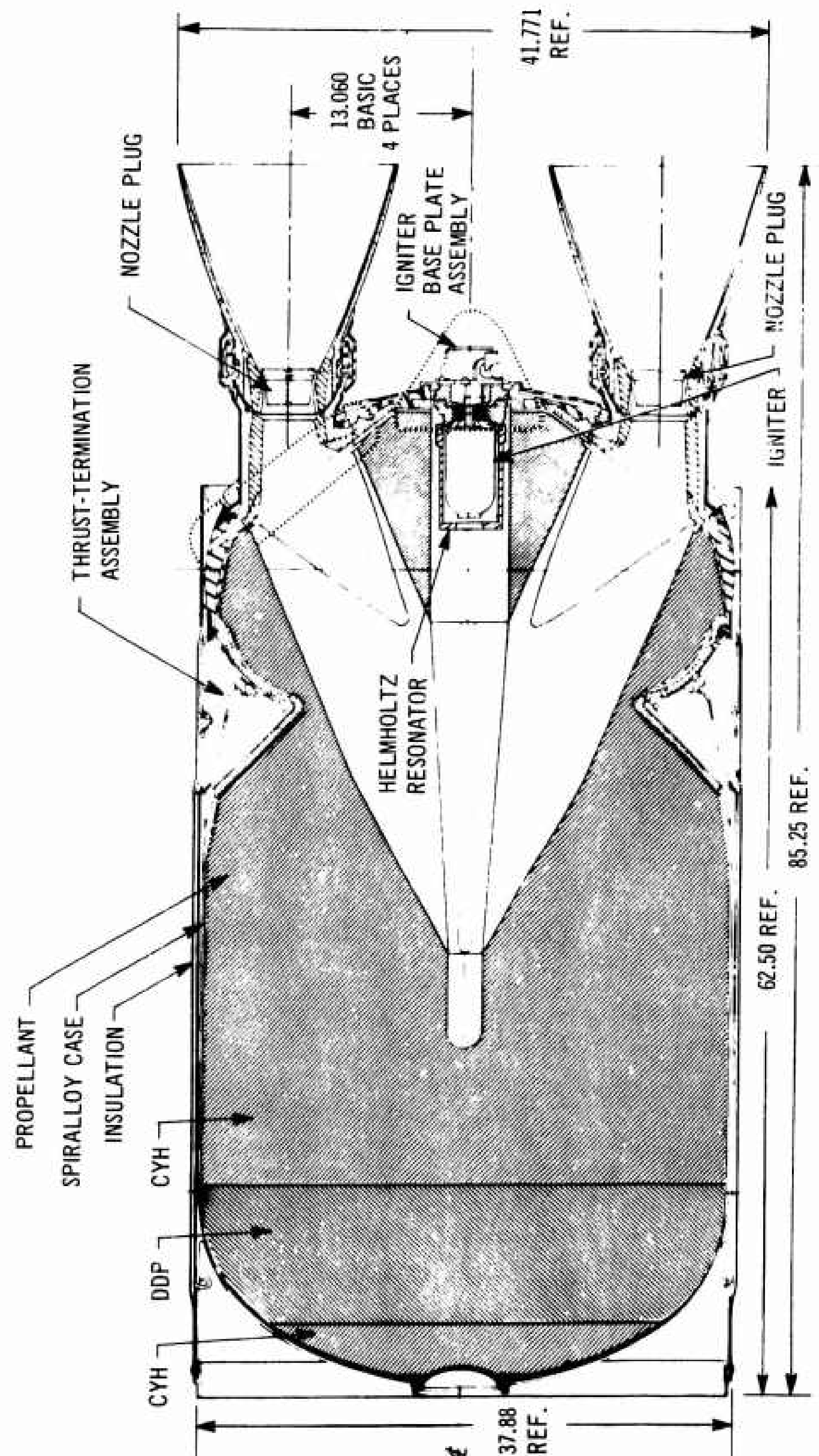


Figure 5. Helmholtz Resonator Installed in Hercules Minuteman III Third Stage Motor (M-57A1)

(U)

SUMMARY AND CONCLUSIONS

(U) This survey has defined numerous applications of mechanical suppression devices in solid rocket motors. Instances where resonance rods have been used far outnumber the applications of the other types of devices (baffles and acoustic cavities). Although the basis for their use has been largely empirical, resonance rods have proven to be generally effective in suppression of high-frequency, transverse, oscillation modes.

(U) Early application of longitudinally oriented baffles (in the so-called "paddle" configuration) apparently evolved from the resonance rod usage. As with resonance rods, the design and installation of these devices has been on an empirical basis. The number of such applications is relatively limited but they have evidently been effective in significantly stabilizing transverse modes. Instances where the longitudinally placed baffle has been evaluated with regard to suppressing axial mode oscillations have not met with success. On the other hand, instances of use of a transversely oriented baffle have indicated effective suppression of axial mode oscillations.

(U) Applications of acoustic cavities to suppress solid rocket combustion instability are fewer even than was the case with baffles. In all instances found their use has been in connection with axial mode instability. Early use involved untuned cavities whose configuration was determined empirically. Even so, effective suppression was indicated in one instance.

(U) Recent use of acoustic cavities has involved tuned Helmholtz resonators. During the very limited activity only moderate success has been achieved in suppressing oscillations; however, there are indications that potentially this type of device can be effectively used. The designs of these acoustic cavities have been based on more substantial theoretical analyses than have the other types of devices. This is due in large measure to the recent advances made with regard to instability suppression in liquid rocket engines.

(U) This survey has clearly indicated that mechanical suppression devices have been effectively used to suppress solid rocket combustion instability. However, it also clearly indicates that these applications have been based on empirical knowledge and experience and that each type of device has limits of application in terms of the characteristics of the motor involved and the instability to be suppressed. It is evident that improved design criteria being evolved in this contract will be extremely valuable to more efficient utilization of mechanical suppression devices.

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